Dynamic pair breaking in cuprate superconductors via injection of spin-polarized quasiparticles in perovskite F-I-S heterostructures

N.-C. Yeh [a,1], J. Y. T. Wei [a], C. C. Fu [a], and R. P. Vasquez [b]

[a] Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA.
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

Abstract

We report experimental evidence of dynamic Cooper pair breaking induced by spin-polarized quasiparticles in cuprate superconductors by studying the critical current density and quasiparticle density of states of ferromagnet-insulator-superconductor (F-I-S) heterostructures. The spin diffusion length and relaxation time are also estimated.

Non-equilibrium superconductivity has been extensively studied since the 1970's [1]. Most of the investigation has focused on the effects of simple quasiparticle (QP) injection and extraction in conventional s-wave superconductors. In contrast, there is insufficient theoretical understanding of spin-polarized QP transport in superconductors, largely due to the complications of combined non-equilibrium [1] and magnetic pair-breaking effects [2] induced by spin-polarized currents. Recently, the concept of spin injection has been investigated in high-temperature superconductors (HTS) by passing an electrical current through a perovskite ferromagnetic manganite to introduce spin-polarized quasiparticles (QP's) [3,4]. However, the reported suppression of critical currents in the perovskite ferromagnet-insulator-superconductor (F-I-S) appear to be primarily induced by Joule heating. To amend this problem, we adopted a pulsed current technique and in-situ thermometry [5], so that the effect of Joule heating is limited to < 10 mK. In this work, we report macroscopic and microscopic experimental evidence of dynamic pair breaking induced by spin-polarized QP currents in perovskite F-I-S heterostructures. These results are compared with control samples of N-I-S heterostructures (N: non-magnetic metal).

The F-I-S and N-I-S samples are fabricated using the pulsed-laser deposition technique [5]. The chemical formulae and thicknesses of the constituent layers are:

- **F:** $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) and $La_{0.7}Sr_{0.3}MnO_3$ (LSMO), 100 nm.
- **I:** $SrTiO_3$ (STO), 2.0 nm; and yttria-stabilized-zirconia (YSZ), 1.3 nm.
- **N:** $LaNiO_3$ (LNO), 100 nm.
- **S:** $YBa_2Cu_3O_7$ (YBCO), 100 nm.

The effect of spin-polarized current I_m on the critical current density (J_c) of YBCO is shown in Figure 1(a), and the absence of effect in the N-I-S sample is illustrated in Figure 1(b). We note that the suppression of J_c in F-I-S becomes significant only

[1] Corresponding author. E-mail: ncyeh@caltech.edu . This work is jointly supported by NSF and NASA/OSS.

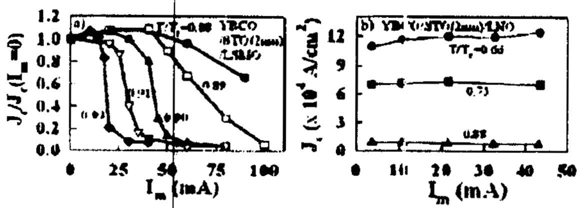

Fig. 1. (a) Effect of the spin-polarized quasiparticle current (I_m) on the J_c of YBCO in an F-I-S heterostructure. (b) Independence of J_c on injection in an N-I-S control sample.

near T_c, due to the diverging QP relaxation time [1]. In analogy to the simple QP relaxation through inelastic electron-phonon scattering [1], we may assume a relaxation process of spin-polarized QP's through the spin exchange interaction. The relaxation time is given by $\tau_s(T) \sim 3.7\tau_{ex}k_BT_c/\langle\Delta(T)\rangle$, where $\tau_{ex} \sim (\hbar/E_{ex})$ is the interaction time associated with the exchange energy $E_{ex} \sim 30$ K in YBCO [5]. Hence, for an average *d*-wave superconducting energy gap $\langle\Delta(T)\rangle \approx \Delta_d[1-(T/T_c)]^{1/2}$ with $\Delta_d \sim 20$ meV, we obtain $\tau_s \sim 3\times10^{-13}[1-(T/T_c)]^{-1/2}$s. The spin diffusion length ℓ_s may be estimated by $\ell_s \approx \sqrt{\ell_0 v_F \tau_s}$, where ℓ_0 is the electron mean free path, and v_F is the Fermi velocity [1]. For $v_F \sim 10^5$ m/s and $\ell_0 \sim 20$ nm, we find that $\ell_s \sim 25$ nm for $T \to 0$ and $\ell_s \sim 80$ nm ($\sim$ sample thickness) at $[1-(T/T_c)] \sim 0.01$. This estimate is consistent with the observed strong dependence of J_c on I_m in F-I-S only near T_c.

The main panel of Figure 2(a) illustrates the differential conductance (dI/dV) versus bias voltage (V) data of YBCO, taken with a low-temperature STM, for c-axis tunneling at 4.2 K and under various I_m. The inset shows the dependence of QP density of states (DOS) on I_m at the Fermi level ($V=0$). The spectra appear invariant for I_m up to 35 mA [6], above which spectral smearing appears, showing excess QP-DOS near the zero bias, which is consistent with Cooper pair breaking. The threshold current $I_m^* \sim 35$ mA corresponds to an injection energy $(eI_m^*R_J) \approx 21$ meV, comparable to Δ_d for a measured junction resistance $R_J \approx 0.6\Omega$. At higher I_m, the QP-DOS may be fitted to an effective QP temperature ($T^* \sim 60$ K), even under negligible Joule heating [6]. In contrast, spec-

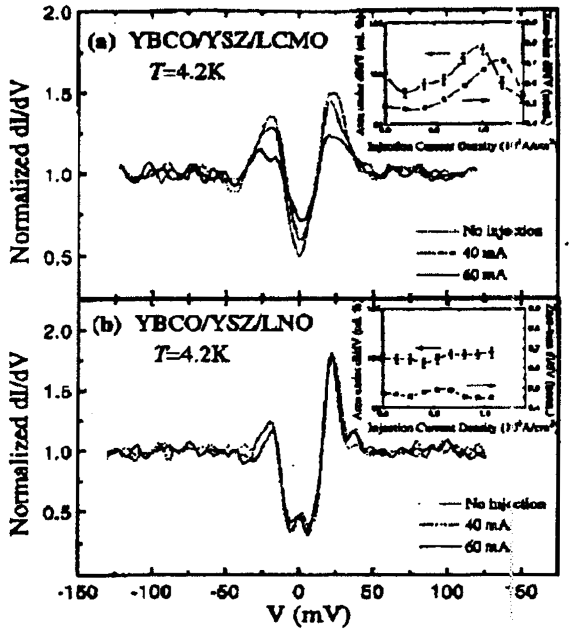

Fig. 2. STM spectroscopy data taken at 4.2 K on (a) F-I-S and (b) N-I-S samples under varying I_m, showing nonconserved spectral area and nonuniform zero-bias conductance for the former, (inset of (a)), and relative spectral invariance for the latter, (inset of (b)).

tral studies of YBCO in the N-I-S sample exhibit no detectable dependence on the injection, as shown in the main panel and the inset of Figure 2(b). These results suggest that spin-polarized QP's are strong "pair breakers". More investigation is underway to determine relevant physical parameters associated with the dynamic pair breaking and quasiparticle tranport in cuprate superconductors.

References

[1] See articles in "*Nonequilibrium Superconductivity, Phonons, and Kapitza Boundaries*", K. E. Gray (ed.), NATO ASI Series, Plenum, New York (1981).

[2] A. A. Abrikosov and L. P. Gor'kov, *Soviet Phys., JETP* **12**, 1243 (1961).

[3] V. A. Vas'ko et al., Phys. Rev. Lett. **78**, 1134 (1997).

[4] Z. W. Dong et al., Appl. Phys. Lett. **71**, 1718 (1997).

[5] N.-C. Yeh et al., preprint, submitted to Phys. Rev. Lett.

[6] J. Y. T. Wei et al., J. Appl. Phys. **85**, 5350 (1999).